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Reviews

Clinical Applications of Arterial Stiffness; Definitions and Reference Values

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Arterial stiffening is the most important cause of increasing systolic and pulse pressure, and for decreasing diastolic pressure beyond 40 years of age. Stiffening affects predominantly the aorta and proximal elastic arteries, and to a lesser degree the peripheral muscular arteries. While conceptually a Windkessel model is the simplest way to visualize the cushioning function of arteries, this is not useful clinically under changing conditions when effects of wave reflection become prominent. Many measures have been applied to quantify stiffness, but all are approximations only, on account of the nonhomogeneous structure of the arterial wall, its variability in different locations, at different levels of distending pressure, and with changes in smooth muscle tone.

This article summarizes the methods and indices used to estimate arterial stiffness, and provides values from a survey of the literature, followed by recommendations of an international group of workers in the field who attended the First Consensus Conference on Arterial Stiffness, which was held in Paris during 2000, under the chairmanship of M.E. Safar and E.D. Frohlich. Am J Hypertens 2002;15:426–444 © 2002 American Journal of Hypertension, Ltd.

Key Words: Arterial stiffening, compliance, distensibility, elastic modulus, wave reflection.

Arterial stiffness is emerging as the most important determinant of increased systolic and pulse pressure in our aging community, and therefore, the root cause of a host of cardiovascular complications and events, including left ventricular hypertrophy and failure, aneurysm formation and rupture, and a major contributor to atherosclerotic and small vessel disease and thus to stroke, myocardial infarction, and renal failure.

Although appreciated for years,[1,2] it is only in recent times, after acceptance of ill effects of systolic pressure in the elderly, that serious attention has been directed at precise measurement of arterial stiffness. The issue, although superficially simple, is complex, as older treatises on the subject will attest.[3–5] The purpose of this review is to introduce the different terms that are used to describe arterial stiffness, and note their pitfalls and limitations and to provide normal values, where possible, as a function of age. Because some terms, which refer to global properties, imply models of the circulation, it will be necessary initially to refer to these models.

Models

The oldest model of the arterial system is the Windkessel—the inverted air-filled dome of old fashioned fire engines that transformed pulsatile flow from a steam or hand-activated pump into a steady stream through the fire hose nozzle (Fig. 1A). In this model, the dome represents the cushioning function of the arteries, and the nozzle, the peripheral resistance.[6] Although conceptually useful, this model is unrealistic because elastic properties are not present at just one site but are distributed along the aorta and major arteries. The pressure wave has a finite wave velocity in arteries, and in addition, pressure waveforms are different in amplitude and contour in central and peripheral arteries.[6] Physical properties of arteries are different as well, and different arteries at different sites respond differently to aging, to hypertension, and to drugs.[7,8] Value of the Windkessel model is seriously limited as a comprehensive explanation of arterial behavior under different circumstances, although under some specific cir-

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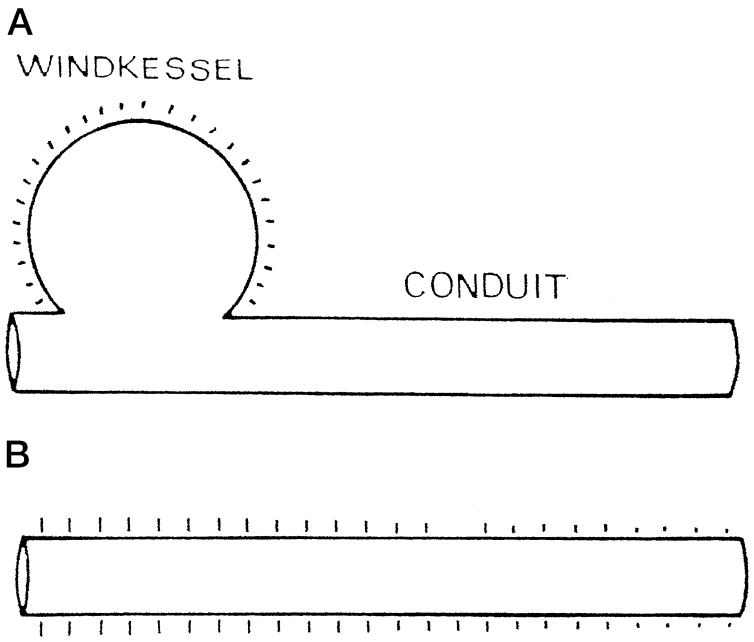

FIG. 1. The cushioning and conduit functions of the arterial system may be represented separately by a proximal Windkessel with peripheral distributing tube (**A**) or by a single distensible tube in which both functions are combined (**B**). (Reprinted with permission from the publisher Churchill Livingstone for O'Rourke MF: Arterial Function in Health and Disease. Edinburgh, 1982).[42] The left end of the tube represents the ascending aorta, and the right end, the summation of all arterial/arteriolar junctions.

cumstances—the very elderly, the very hypertensive—it may appear realistic.

The most realistic model of the arterial system is a simple tube with one end representing the peripheral resistance, and with the other end, receiving blood in spurts from the heart (Fig. 1).[6] A wave generated by cardiac activity travels along the tube toward the periphery and is reflected back from the periphery. The pressure wave at any point along the tube is a resultant of incident and reflected wave. When the tube is distensible, as in youth, the wave velocity is slow, therefore reflection returns late to the heart, in diastole. When the tube wall is stiffened, as in the elderly, wave travel is fast, and the reflected wave merges with the systolic part of the incident wave, causing a high pressure in systole and corresponding low pressure in diastole throughout the tube (Fig. 2).[6]

Indices of Arterial Stiffness

A host of indices have been introduced to quantify arterial stiffness. As is usual when multiple indices exist, no one has proved superior, and all have problems in measurement and interpretation. The subject was addressed at the Satellite of the 1994 International Society of Hypertension (ISH) Meeting in Sydney, and this list of indices was put forward, and agreed to as an interim measure[9,10] (Table 1). There are reservations on many of these indices, because they are influenced by one or more of the following: A. use of inappropriate arterial model (eg, Windkessel); B. assume values of cardiac output that are not, or poorly validated; C. relate proximal diameter change to pressure change at a distant site; and D. are influenced by heart rate or cardiac contractility.

An example of C is that three articles in major cardiologic journals during 1999 relate diameter change in the aorta to systolic pressure in the brachial artery, thus ignoring the variable amplification of the pressure pulse wave between central and peripheral arteries.[11–13]

Likewise the widely quoted Heart Outcomes Prevention Evaluation study implies that brachial systolic pressure is an appropriate measure of central systolic pressure and of left ventricular load.[14,15] These practical problems aside, there are fundamental problems in application of physical terms to arterial stiffness. The arterial media is a mix of collagen and elastin with consequent nonlinear relationship between pressure and diameter. Hence, stiffness can only be quantified at a given level of pressure as the tangent to a curve.[6,16] Furthermore, collagen and elastin are linked by smooth muscle whose activity modulates the contribution of each to arterial stiffness; hence, measured stiffness varies with smooth muscle tone—as effected by nervous activity, by hormones, or locally produced vasoactive substances including nitric oxide released from the vascular endothelium or by drugs.[8,17–19] Furthermore still, because the arterial wall is nonhomogenous, application of terms such as Young's modulus, which considers wall thickness, but assumes homogeneity of the wall, may be unrealistic. Finally, muscular arteries show spontaneous vasomotor changes that cause changes in diameter and wall stiffness.[20,21] These play havoc with attempts to determine elastic properties in individual arteries. Such spontaneous changes, which are seen also in

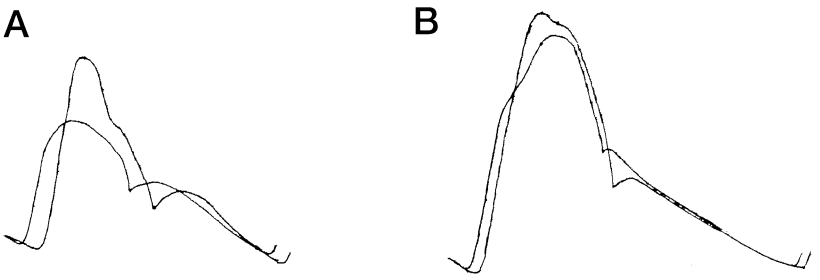

FIG. 2. Pressure waves shown schematically in the ascending aorta and radial artery (delayed tracing) of a young adult (**A**) and older human subject (**B**).

the arteriolar network, do not appear to the same extent in the aorta and large elastic arteries. Because they appear to be out of phase in different peripheral arterial beds, they appear to have little effect on global indices such as those derived from pulse wave contour.

The seminal studies on arterial stiffness were performed by Bergel[3,4] on exteriorized arterial segments. These studies were extended by Gow and other researchers, with the field summarized by Gow in the *Handbook of Physiology*.[5] In principle, these studies did not consider change in smooth muscle tone, as is seen clinically, on arterial stiffness,[8,17–19] but did note the complicated interpretations of arterial stiffness with change in arterial caliber and in arterial pressure. Of particular difficulty was the issue of "initial length" of load-bearing elements, as used to determine elastic modulus and distensibility.

Direct Measurement

Direct measurement of arterial stiffness relates measurement of change in arterial diameter and pressure at the same site. This can be accomplished invasively with the

Table 1. Definition and units of the various indices of arterial stiffness

Arterial distensibility	Relative diameter (or area) change for a pressure increment; the inverse of elastic modulus $\Delta D/\Delta P \cdot D)$ (mm Hg^{-1})
Arterial compliance	Absolute diameter (or area) change for a given pressure step at fixed vessel length $\Delta D/\Delta P$ (cm/mm Hg) or cm^2/mm Hg)
Volume elastic modulus	Pressure step required for (theoretical) 100% increase in volume $\Delta P/(\Delta V/V)$ (mm Hg) = $\Delta P/(\Delta D/D)$ (mm Hg) where there is no change in length
Elastic modulus	The pressure step required for (theoretical) 100% stretch from resting diameter at fixed vessel length $(\Delta P \cdot D/\Delta D)$ (mm Hg)
Young's modulus	Elastic modulus per unit area; the pressure step per square centimeter required for (theoretical) 100% stretch from resting length $\Delta P \cdot D/(\Delta D \cdot h)$ (mm Hg/cm)
Pulse wave velocity	Speed of travel of the pulse along an arterial segment Distance/ Δt (cm/s)
Pressure augmentation	Increase in aortic or carotid pressure after the peak of blood flow in the vessel (mm Hg or as % of pulse pressure)
Characteristic impedance	Relationship between pressure change and flow velocity in the absence of wave reflections $(\Delta P/\Delta V)$ [(mm Hg/cm)/s]
Stiffness index	Ratio of logarithm (systolic/diastolic pressures) to (relative change in diameter) β = In (Ps/Pd) / [(Ds − Dd)/Dd] (nondimensional)
"Large artery elasticity index"	Relationship between pressure fall and volume fall in the arterial tree during the exponential component of diastolic pressure decay $\Delta V/\Delta P$ (cm^3/mm Hg)
Small artery elasticity index	Relationship between oscillating pressure change and oscillating volume change around the exponential pressure decay during diastole $\Delta V/\Delta P$ (cm^3/mm Hg)

P = pressure; D = diameter; V = volume; h = wall thickness; t = time; s = systolic; d = diastolic.

Table 2. Indices of arterial stiffness and reference values

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
Elastic modulus*	Ao arch	Healthy	Av. 33	M/F	118/76	0.526	Isnard et al 1989[48]	Unit: Nxm^{-2}
The pressure step required for	Ao arch	Healthy	Av. 14	N/A	116/71	23.2	Ong et al 1992[49]	Unit: kPa
(theoretical) 100% stretch	Ao arch	Healthy	Av. 62	M/F	130/77	123	Gatzka et al 1998[50]	Unit: $kNxm^{-2}$
from resting diameter at	Ao arch	CAD	Av. 63	M/F	133/74	212	Gatzka et al 1985[50]	
fixed vessel length (ΔP×D)/	Ao arch	Hypertensives	Av. 38	M/F	160/102	1.071	Isnard et al 1989[48]	Unit: Nxm^{-2}
DD (mm Hg)	Ao arch	Postcoartectomy	Av. 13	N/A	122/72	42.1	Ong et al 1992[49]	Unit: kPa
	Desc. thoracic Ao	Various	Av. 53	M/F	124/74	1.19	Pasierski et al 1994[51]	Unit: dynes × $10^6/cm^2$
	Desc. thoracic Ao	Various	Av. 55	M/F	91.5 (mean)	1.032	Lang et al 1994[52]	Unit: dynes × $10^6/cm^2$
	Desc. thoracic Ao	Healthy	Av. 47	M	125/78	0.76	Pearson et al 1994[53]	Unit: dynes × $10^6/cm^2$
	Desc. thoracic Ao	Healthy	Av. 43	F	123/75	0.68	Pearson et al 1994[53]	Unit: dynes × $10^6/cm^2$
	Desc. thoracic Ao	Hypertensives	Av. 47	M/F	150/92	0.98	Pearson et al 1994[53]	Unit: dynes × $10^6/cm^2$
	Abdominal Ao	Healthy	Av. 25	M	117/70	0.69	Lanne et al 1992[54]	Unit: dynes × $10^6/cm^2$
	Abdominal Ao	Healthy	Av. 27	F	120/76	0.52	Sonesson et al 1993[55]	Unit: dynes × $10^5/cm^2$
	Abdominal Ao	Healthy	20–39	N/A	120/69	0.736	Kawasaki et al 1987[56]	Unit: dynes × $10^6/cm^2$
	Abdominal Ao	Healthy	Av. 60	N/A	124/74	1.1	Hirai et al 1989[26]	Unit: dynes × $10^6/cm^2$
	Abdominal Ao	CAD	Av. 55–59	M/F	128–140/ 79–83	1.62–3.08	Harai et al 1989[26]	Unit: dynes × $10^6/cm^2$ 4 subgroups: no stenosis 3-vessel disease
	C	Healthy	20–39	N/A	117/70	0.7	Kawasaki et al 1987[56]	Unit: dynes × $10^6/cm^2$
	C	Normotensives	Av. 56	M/F	113/69	124	Liao et al 1999[11]	Unit: kPa
	C	Normotensives	Av. 47	M/F	115/71	0.71 (effective)/ 1.16 (intrinsic)	Bussy et al 2000[57]	Unit: kPa × 10^3
	C	Healthy	Av. 60	N/A	124/74	1.21	Hirai et al 1989[26]	Unit: dynes × $10^6/cm^2$
	C	CAD	Av. 55–59	M/F	128–140/ 79–83	1.23–1.84	Hirai et al 1989[26]	Unit: dynes × $10^6/cm^2$ 4 subgroups: no stenosis 3-vessel disease
	C	Hypertensives	Av. 56	M/F	124/74	155	Liao et al 1999[11]	Measured at baseline before development of hypertension Unit kPa
	C	Hypertensives	Av. 50	M/F	153/99	1.04 (effective)/ 1.02 (intrinsic)	Bussy et al 2000[57]	Unit: kPa × 10^3
	B	Healthy	20–39	N/A	116/69	0.94	Kawasaki et al 1987[56]	Unit: dynes × $10^6/cm^2$
	Fem	Healthy	20–39	N/A	116/68	1.15	Kawasaki et al 1987[56]	Unit: dynes × $10^6/cm^2$

(*continued*)

Table 2. Continued

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
Arterial distensibility* Relative diameter (or area) change for a pressure increment; the inverse of elastic modulus $\Delta D/(\Delta P \times D)$ mm Hg^{-1}	Asc. Ao	Healthy	Av. 45	M	120/70	3.96	Stefanadis et al 1990[58]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Asc. Ao	Healthy	Av. 29	M/F	122/75	5.6	Hirata et al 1991[59]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Asc. Ao	Normotensive	Av. 49	M/F	119/74	7.0	Resnick et al 1997[60]	Unit: $10^{-3} \times mm\ Hg^{-1}$
	Asc. Ao	CAD	Av. 46	M	118/67	1.60	Stefanadis et al 1990[58]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Asc. Ao	Marfan S.	Av. 26	M/F	126/81	2.9	Hirata et al 1991[59]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Asc. Ao	Chronic Ao Regurg.	Av. 40	M/F	127/60	0.17	Wilson et al 1992[61]	Unit: $10^{-2} \times mm\ Hg^{-1}$
	Asc. Ao	Hypertensive	Av. 50	M/F	149/93	2.5	Resnick et al 1997[60]	Unit: $10^{-3} \times mm\ Hg^{-1}$
	Desc. thoracic Ao	Healthy	Av. 53	M/F	122/76	3.5	Stefanadis et al 1997[62]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Desc. thoracic Ao	Healthy	Av. 50	M	119/75	3.95	Stefanadis et al 1995[22]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Desc. thoracic Ao	Normotensive	Av. 49	M/F	119/74	5.1	Resnick et al 1997[60]	Unit: $10^{-3} \times mm\ Hg^{-1}$
	Desc. thoracic Ao	Hypertensive	Av. 54	M/F	176/98	1.4	Stefanadis et al 1997[62]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Desc. thoracic Ao	Hypertensive	Av. 50	M/F	149/93	2.2	Resnick et al 1997[60]	Unit: $10^{-3} \times mm\ Hg^{-1}$
	Desc. thoracic Ao	CAD	Av. 55	M	125/74	1.73	Stefanadis et al 1995[22]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Abdominal Ao	Healthy	Av. 29	M/F	122/75	7.7	Hirata et al 1991[59]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times 10^{-6}$
	Abdominal Ao	Normotensive	Av. 49	M/F	119/74	7.3	Resnick et al 1997[60]	Unit: $10^{-3} \times mm\ Hg^{-1}$
	Abdominal Ao	Healthy	Av. 36	M/F	114/68	20.5	Jondeau et al 1999[63]	Unit: $10^{-3} \times kPa$
	Abdominal Ao	Healthy	Av. 34	M/F	128/77	~0.39	Giannattasio et al 1999[64]	Multiplication by 2 Unit: $10^{-2} \times mm\ Hg^{-1}$
	Abdominal Ao	Diabetics type I no complications	Av. 32	M/F	128/76	~0.335	Giannattasio et al 1999[64]	Multiplication by 2 Unit: $10^{-2} \times mm\ Hg^{-1}$
	Abdominal Ao	Diabetics type I complications	Av. 38	M/F	145/782	~0.25	Giannattasio et al 1999[64]	Multiplication by 2 Unit: $10^{-2} \times mm\ Hg^{-1}$
	Abdominal Ao	Marfan	Av. 26	M/F	126/81	5.5	Hirata et al 1991[59]	Multiplication by 2 Unit: $cm^2 \times dynes^{-1} \times \times 10^{-6}$

(*continued*)

Table 2. Continued

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
	Abdominal Ao	Hypertensive	Av. 50	M/F	149/93	2.3	Resnick et al 1997[60]	Unit: $10^{-3} \times$ mm Hg^{-1}
	Abdominal Ao	Marfan	Av. 37	M/F	110/64	12.7	Jondeau et al 1999[63]	Unit: $10^{-3} \times$ kPa
	C	Healthy	Av. 50	M/F	118/71	11.7 (effective)/ 9.0 (intrinsic)	Laurent et al 1994[65]	Unit: $10^{-3} \times$ /kPa
	C	Healthy	Av. 28	M/F	~108/63	~0.35	Faila et al 1997[66]	Divided by 2 and multiplied by π Unit: $10^{-3} \times$ mm Hg^{-1}
	C	Healthy	Av. 38	M/F	—	22.8	Kool et al 1994[67]	Multiplied by 2 π Unit: $10^{-3} \times$ /kPa^{-1}
	C	Healthy	Av. 36	M/F	114/68	43.3	Jondeau et al 1999[63]	Unit: $10^{-3} \times$ /kPa
	C	Hypertensive	Av. 51	M/F	156/93	7.8 (effective)/ 10 (intrinsic)	Laurent et al 1994[65]	Unit: $10^{-3} \times$ /kPa
	B	Random population sample	Av. 50	M	132/84	20.9	van der Heijden-Spek et al 2000[68]	Unit: $10^{-3} \times$ /kPa
	B	Random population sample	Av.50	F	128/81	24.4	van der Heijden-Spek et al 2000[68]	Unit: $10^{-3} \times$ /kPa
	B	Healthy	Av.38	—	—	5.05	Bank & Kaiser 1998[8]	at 95 mm Hg Unit: mm Hg^{-1}
	B	Healthy	Av. 38	M/F	—	30.5	Kool et al 1994[67]	Multiplied by 2π Unit: $10^{-3} \times$ kPa^{-1}
	R	Normotensive	Av.36–41	M/F	121–141/ 66–77	(0.67–1.00)* (0.50–0.90)†	Laurent et al 1993[69]	Multicenter study; *at mean pressure; †at 100 mm Hg Unit: $10^{-3} \times$ mm Hg^{-1}
	R	Healthy	Av. 28	M/F	~108/63	~0.84	Faila et al 1997[66]	Divided by 2 and multiplied by π Unit: $10^{-3} \times$ mm Hg^{-1}
	R	Healthy	Av. 55	M/F	127/68	~1.4	Giannattasio et al 1997[70]	Langewouters formula Unit: mm/mm Hg 10^{-3}
	R	Healthy	Av. 36	M/F	114/68	5.0	Jondeau et al 1999[63]	Unit: 10^{-3} kPa^{-1}
	R	Hypertensives	Av. 43–50	M/F	163–172/ 81–103	(0.41–0.91)* (0.71–1.10)†	Laurent et al 1993[69]	Multicenter study; *at mean pressure; †at 100 mm Hg; unit: $10^{-3} \times$ mm Hg^{-1}
	R	Hypothyroidism	Av. 59	M/F	129/69	~1.85	Giannattasio et al 1997[70]	Langewouters formula Unit: mm/mm Hg 10^{-3}
	F	Healthy	Av. 38	M/F	—	21	Kool et al 1994[67]	Multiplied by 2π Unit: $10^{-3} \times$ kPa^{-1}
	F	Healthy	Av. 36	M/F	114/68	7.7	Jondeau et al 1999[63]	Unit: 10^{-3} kPa^{-1}
	Desc. thoracic Ao	Various	Av. 55	M/F	92 (mean)	0.010	Lang et al 1994[52]	Unit: cm^2/mm Hg
Arterial compliance*								
Absolute diameter (or area) change for a given pressure step at a fixed vessel length $\Delta D/(\Delta P)$ cm $\times$ mm Hg^{-1}	Abdominal Ao	Healthy	Av. 36	M/F	114/68	27.7	Jondeau et al 1999[63]	Unit: m$^2 \times$ kPa$^{-1} \times 10^{-7}$
	Abdominal Ao	Marfan	Av. 37	M/F	110/64	21.6	Jondeau et al 1999[63]	Unit: m$^2 \times$ kPa$^{-1} \times 10^{-7}$
	C	Healthy	Av. 38	M/F	—	0.84	Kool et al 1994[67]	Multiplied by 2, divided by π Unit: mm$^2 \times$ kPa^{-1}

(*continued*)

Table 2. Continued

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
	C	Healthy	Av. 50	M/F	118/71	8.72 (effective)/ 6.9 (intrinsic)	Laurent et al 1994[65]	Unit: $m^2 \times kPa^{-1} \times 10^{-7}$
	C	Healthy	Av. 36	M/F	114/68	8.55	Jondeau et al 1999[63]	Unit: $m^2 \times kPa^{-1} \times 10^{-7}$
	C	Hypertensive	Av. 51	M/F	156/93	6.31 (effective)/ 7.8 (intrinsic)	Laurent et al 1994[65]	Unit: $m^2 \times kPa^{-1} \times 10^{-7}$
	B	Healthy	Av. 38	—	—	0.010	Bank & Kaiser 1998[8]	at 95 mm Hg Unit: mm^2/mm Hg
	B	Healthy	Av. 38	M/F	—	0.47	Kool et al 1994[67]	Multiplied by 2, divided by π Unit: $mm^2 \times kPa^{-1}$
	B	Random population sample	Av. 50	M	132/84	0.33	van der Heijden-Spek et al 2000[68]	Unit: mm^2/kPa
	B	Random population sample	Av. 50	F	128/81	0.25	van der Heijden-Spek et al 2000[68]	Unit: mm^2/kPa
	R	Normotensive	Av. 36–41	M/F	121–141/ 66–77	(3.23–4.58)* (2.8–3.4)†	Laurent et al 1993[69]	Multicenter study; *at mean pressure; †at 100 mm Hg Unit: $10^{-3} \times mm^2 \times mm\ Hg^{-1}$
	R	Healthy	Av. 53	M/F	117/64	~5.7	Giannattasio et al 1995[71]	Langewouters formula Unit: mm^2/ mm Hg 10^{-3}
	R	Healthy	Av. 48	M/F	121/73	1.81	Mourad et al 1998[72]	Unit: $m^2 \times kPa^{-1} \times 10^{-8}$
	R	Healthy	Av. 36	M/F	114/68	0.22	Jondeau et al 1999[63]	Unit: $m^2 \times kPa^{-1} \times 10^{-7}$
	R	Hypertensives	Av. 43–50	M/F	163–172/ 81–103	(2.61–4.81)† (3.4–6.8)†	Laurent et al 1993[69]	Multicenter study; *at mean pressure; †at 100 mm Hg Unit: $10^{-3} \times mm^2 \times mm\ Hg^{-1}$
	R	Hypertensive	Av. 57	M/F	179/100	~7	Giannattasio et al 1997[73]	Langewouters formula Isobaric Unit: mm^2/mm Hg 10^{-3}
	R	Hypertension (hypertrophied artery)	Av. 50	M/F	163/99	1.82	Mourad et al 1998[72]	Unit: $m^2 \times kPa^{-1} \times 10^{-8}$
	R	Hypertension (remodeled artery)	Av. 49	M/F	166/99	1.03	Mourad et al 1998[72]	Unit: $m^2 \times kPa^{-1} \times 10^{-8}$
	R	Hypercholesterolemia	Av. 47	M/F	107/60	~2.5	Giannattasio et al 1997[74]	Langewouters formula Unit: mm^2/mm Hg 10^{-3}
	R	Congestive heart failure	Av. 57	M/F	106/62	~4.15	Giannattasio et al 1995[71]	Langewouters formula Unit: mm^2/mm Hg 10^{-3}
	F	Healthy	Av. 38	M/F	—	1.28	Kool et al 1994[67]	Multiplied by 2, divided by π Unit: $mm^2 \times kPa^{-1}$
	F	Healthy	Av. 36	M/F	114/68	5.3	Jondeau et al 1999[63]	Unit: $m^2 \times kPa^{-1} \times 10^{-7}$

(*continued*)

Table 2. Continued

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
Young's modulus* Elastic modulus per unit area; the pressure step per 4 square centimeter required for (theoretical) 100% strech from resting length $\Delta P \times D/(\Delta D \times h)$ (mm Hg/cm)	Desc. thoracic Ao	Healthy	Av. 47	M	125/78	7.37	Pearson et al 1994[53]	Unit: dynes $\times 10^6/cm^2$
	Desc. thoracic Ao	Healthy	Av. 43	F	123/75	6.03	Pearson et al 1994[53]	Unit: dynes $\times 10^6/cm^2$
	Desc. thoracic Ao	Hypertensives	Av. 47	M/F	150/92	13.88	Pearson et al 1994[53]	Unit: dynes $\times 10^6/cm^2$
	C	Normotensives	Av. 56	M/F	113/69	678	Liao et al 1999[11]	Unit: kPa
	C	Hypertensives	Av. 56	M/F	124/74	822	Liao et al 1999[11]	Measured at baseline before development of hypertension Unit: kPa
Pulse wave velocity* Speed of travel of the pulse along an arterial segment Distance/Δt (cm/s)	Asc. Ao	Healthy	Av. 34	M/F	117/77	668	Murgo et al 1980[75]	
	Asc. Ao	Healthy (majority)	Av. 38	M/F	—	387	Merillon et al 1976[76]	
	Asc. Ao	Hypertensives	Av. 32	M/F	—	570	Merrillon et al 1976[76]	
	Asc. Ao	Healthy	Av. 42	M/F	Mean 91	440	Latham et al 1985[77]	
	Thoracic Ao	Healthy	Av. 42	M/F	Mean 91	530	Latham et al 1985[77]	
	Abdominal Ao	Healthy	Av. 42	M/F	Mean 91	570	Latham et al 1985[77]	
	Iliac	Healthy	Av. 42	M/F	Mean 91	880	Latham et al 1985[77]	
	B	Healthy	Av. 38	—	—	1510	Bank & Kaiser 1998[8]	at 95 mm Hg
	Ao Arch to Fem	Healthy/low prevalence of Hypertensive	Av. 46 (approx)	M/F	—	$= 5.1 \times$ age + 533	Avolio et al 1985[78]	Site to site
	Ao Arch to Fem	Healthy/high prevalence of Hypertensive	Av. 46 (approx)	M/F	—	$=9.2 \times$ age + 615	Avolio et al 1985[78]	Site to site
	Asc. Ao or C-Fem	Healthy Elderly	Av. 70	M/F	140/73	906	Chen et al 1999[79]	Suprastenal notch to femoral
	Ao Arch or C-Fem	End-stage renal disease	Av. 52	M/F	157/85	1110	Blacher et al 1999[80]	Site to site or distance subtraction
	C-Fem	Healthy	Av. 33	M/F	118/76	890	Isnard et al 1989[48]	Site to site
	C-Fem	Healthy whites	Av. 25	M	120/78	815	Ferreira et al 1999[81]	Site to site
	C-Fem	Healthy African Americans	Av. 23	M	119/77	775	Ferreira et al 1999[81]	Site to site
	C-Fem	Healthy	Av. 24	M	118/68	620	Kingwell et al 1997[82]	Distance subtraction
	C-Fem	Healthy	Av. 29	M/F	122/75	950	Hirata et al 1991[59]	Site to site
	C-Fem	Healthy	Av. 52	M/F	141/82	930	London et al 1992[8]	Distance subtraction
	C-Fem	Healthy	Av. 62	M/F	143/89	980	Breithaupt-Grogler et al 1997[83]	Site to site
	C-Fem	Random population sample no cardiovasc. Treatment or complication	Av. 46	M/F	98–222/ 62–130	$=0.07 \times$ SP$+0.09 \times$ age-4.3	Asmar et al 1995[84]	Site to site
	C-Fem	Normotensives	Av. 45	M/F	125/77	$=0.06 \times$ age$+5.7 \times 10^2$	Asmar et al 1995[85]	Site to site

(*continued*)

Table 2. Continued

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
	C-Fem	Random population sample	Av. 50	M	132/84	700	van der Heijden-Spek et al 2000[68]	Distance subtraction
	C-Fem	Random population sample	Av. 50	F	128/81	670	van der Heijden-Spek et al 2000[68]	Distance subtraction
	C-Fem	Hypertensive	Av. 38	M/F	160/102	1180	Isnard et al 1989[48]	Site to site
	C-Fem	Hypertensives treated	Av. 59	M/F	144/82	$=0.11 \times age + 3.5 \times 10^2$	Asmar et al 1995[85]	Site to site
	C-Fem	Hypertensives untreated	Av. 48	M/F	164/102	$=0.12 \times age + 6.3 \times 10^2$	Asmar et al 1995[85]	Site to site
	C-Fem	Hypertensive no vasc. Dis	Av. 57	M/F	144/83	1240	Bortolotto et al 1999[86]	Site to site
	C-Fem	Hypertensive no vasc. Dis.	Av. 62	M/F	148/83	1430	Bortolotto et al 1999[86]	Site to site
	C-Fem	Hypertensive whites	Av. 28	M	151/94	880	Ferreira et al 1999[81]	Site to site
	C-Fem	Hypertensive African Americans	Av. 29	M	152/97	930	Ferreira et al 1999[81]	Site to site
	C-Fem	Hypertensive no atherosclerosis	Av. 57	M/F	144/84	1240	Blacher et al 1999[87]	Site to site
	C-Fem	Hypertensive atherosclerosis	Av. 67	M/F	149/80	1490	Blacher et al 1999[87]	Site to site
	C-Fem	Marfan	Av. 26	M/F	126/81	1160	Hirata et al 1991[59]	Distance subtraction
	C-Fem	Chronic uremia	Av. 53	M/F	153/81	1035	London et al 1992[28]	Site to site
	B-R	Healthy	Av. 39	M	132/78	880	Armentano et al 1991[88]	Site to site
	B-R	Healthy/low prevalence of hypertension	Av. 46 (approx)	M/F	—	$=0.61 \times age + 817$	Avolio et al 1985[78]	Site to site
	B-R	Healthy/high prevalence of hypertension	Av. 46 (approx)	M/F	—	$=4.8 \times Age + 998$	Avolio et al 1985[78]	Site to site
	B-R	Normotensives	Av. 40	M	132/78	880	Simon et al 1985[89]	Site to site
	B-R	Hypertensives	Av. 43	M	168/98	1150	Simon et al 1985[89]	Site to site
	B-R	Hypertensive	Av. 43	M	168/98	1160	Armentano et al 1991[88]	Site to site
	Fem-foot	Healthy/low prevalence of hypertension	Av. 46 (approx)	M/F	—	$=4.43 \times Age + 718$	Avolio et al 1985[78]	Site to site
	Fem-foot	Healthy/high prevalence of hypertension	Av. 46 (approx)	M/F	—	$=5.6 \times Age + 791$	Avolio et al 1985[78]	Site to site
	Fem-foot	Healthy	Av. 24	M	118/68	830	Kingwell et al 1997[82]	Site to site

(*continued*)

Table 2. Continued

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
Characteristic impedance*	Asc. Ao	Healthy	Av. 34	M/F	117/77	47	Murgo et al 1980[75]	Unit: dyne · s · cm^{-5}
Relationship between pressure change and flow velocity in the absence of wave reflections $\Delta P/\Delta v$ (mm Hg)(cm × s)	Asc. Ao	Healthy (majority)	Av. 38	M/F	—	73	Merillon et al 1976[76]	Unit: dyne · s · cm^{-5}
	Asc. Ao	CAD (majority)	Av. 47	—	100 (mean)	97	O'Rourke and Avolio 1980[90]	Unit: dyne · s · cm^{-5}
	Asc. Ao	Healthy (majority)	Av. 42	M/F	121/78	94	Ting et al 1986[34]	Unit: dyne · s · cm^{-5}
	Asc. Ao	Hypertensives	Av. 35	M/F	168/99	146	Ting et al 1986[34]	Unit: dyne · s · cm^{-5}
	Asc. Ao	CAD	Av. 56	M/F	126/71	136	Kelly and Fitchett 1992[91]	Unit: dyne · s · cm^{-5}
	Asc. Ao	Hypertensives	Av. 32	M/F	—	81	Merrillon et al 1976[76]	Unit: dyne · s · cm^{-5}
	Asc. Ao	Heart failure	21–70	M/F	89 (mean)	138	Binkley et al 1990[92]	Unit: dyne · s · cm^{-5}
Stiffness index	Asc. Ao	Healthy	Av. 29	M/F	112/75	5.9	Hirata et al 1991[59]	
Ratio of logarithm (systolic/diastolic pressures) to (relative change in diameter) β=ln $(P_s/P_d)/[(D_s-D_d)/D_d]$ nondimensional	Asc. Ao	Marfan	Av. 26	M/F	126/81	10.9	Hirata et al 1991[59]	
	Ao arch	Healthy	Av. 14	N/A	116/71	2.17	Ong et al 1992[49]	Did not divide by D_d?
	Ao arch	Healthy	Av. 62	M/F	130/77	9	Gatzka et al 1998[50]	
	Ao arch	CAD	Av. 63	M/F	133/74	16	Gatzka et al 1998[50]	
	Ao arch	Post coartectomy	Av. 13	N/A	122/72	3.66	Ong et al 1992[49]	Did not divide by D_d?
	Desc. thoracic Ao	Various	Av. 53	M/F	124/74	3.77	Pasierski et al 1994[51]	
	Desc. thoracic Ao	Healthy	Av. 47	M	125/78	5.71	Pearson et al 1994[53]	
	Desc. thoracic Ao	Healthy	Av. 43	F	123/75	5.10	Pearson et al 1994[53]	
	Desc. thoracic Ao	Hypertensives	Av. 47	M/F	150/92	13.88	Pearson et al 1994[53]	
	Abdominal Ao	Healthy	6-81	N/A	Normotensive	4.29–9.83	Kawasaki et al 1987[56]	4 different age groups
	Abdominal Ao	Healthy	Av. 29	M/F	112/75	3.9	Hirata et al 1991[59]	
	Abdominal Ao	Healthy	Av. 60	N/A	124/74	8.58	Hirai et al 1989[26]	
	Abdominal Ao	CAD	Av. 55–59	M/F	128–140/79–83	12.25–22.37	Hirai et al 1989[26]	4 subgroups: no stenosis 3-vessel disease
	Abdominal Ao	Marfan	Av. 26	M/F	126/81	7.1	Hirata et al 1991[59]	
	C	Healthy	6–81	N/A	Normotensive	4.32–11.31	Kawasaki et al 1987[56]	4 different age groups
	C	Normotensives	Av. 56	M/F	113/69	10.3	Liao et al 1999[11]	
	C	Healthy	Av. 60	N/A	124/74	9.17	Hirai et al 1989[26]	
	C	CAD	Av. 55–59	M/F	128–140/79–83	9.42–13.17	Hirai et al 1989[26]	4 subgroups: no stenosis 3-vessel disease
	C	Hypertensives	Av. 56	M/F	124/74	11.87	Liao et al 1999[11]	Measured at baseline before development of hypertension
	B	Healthy	6–81	N/A	Normotensive	8.56–13.73	Kawasaki et al 1987[56]	4 different age groups
	F	Healthy	6–81	N/A	Normotensive	9.41–15.31	Kawasaki et al 1987[56]	4 different age groups

(*continued*)

Table 2. Continued

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
Capacitative compliance Relationship between pressure fall and volume fall in the arterial tree during the exponential component of diastolic pressure decay $\Delta V/\Delta P$ (cm^3/mm Hg)	Proximal part of circulation	Normotensive	Av. 47	M/F	115/63	~2.2	Cohn et al 1995[24]	
	Proximal part of circulation	Healthy	Av. 50	—	138/75	1.71	Duprez et al 1998[93]	
	Proximal part of circulation	Healthy	21–80 (M)/ 22–83 (F)	M/F	125/68 & 120/66	~2(M)/1.7(F)	McVeigh et al 1999[33]	
	Proximal part of circulation	Heart failure	Av. 59	—	116/69	1.51	Duprez et al 1998[93]	
	Proximal part of circulation	Hypertensive	Av. 54	M/F	152/86	~1.95	Cohn et al 1995[24]	
	Proximal part of circulation	No CAD	Av. 53	F	123/68	~1.8	Cohn et al 1995[24]	
	Proximal part of circulation	CAD	Av. 55	F	132/70	~1.8	Cohn et al 1995[24]	
Oscillatory compliance Relationship between oscillating pressure change and oscillating volume change around the exponential pressure decay during diastole $\Delta V/\Delta P$ (cm^3/mm Hg)	Distal part of circulation	Normotensive	Av. 47	M/F	115/63	~0.075	Cohn et al 1995[24]	
	Distal part of circulation	Healthy	Av. 50	—	138/75	0.054	Duprez et al 1998[93]	
	Distal part of circulation	Healthy	21–80 (M)/ 22–83(F)	M/F	125/68 & 120/66	~0.08(M)/ 0.056(F)	McVeigh et al 1999[33]	
	Distal part of circulation	Heart failure	Av. 59	—	116/69	0.050	Duprez et al 1998[93]	
	Distal part of circulation	Hypertensive	Av. 54	M/F	152/86	~0.05	Cohn et al 1995[24]	
	Distal part of circulation	No CAD	Av. 53	F	123/68	~0.065	Cohn et al 1995[24]	
	Distal part of circulation	CAD	Av. 55	F	132/70	~0.05	Cohn et al 1995[24]	
Total arterial compliance "Area method"	Whole body	Normotensive	Av. 43	N/A	120/77	1.47	Liu et al 1989[94]	At mean pressure Units: mL/mm Hg
	Whole body	Hypertensive	37	N/A	166/99	0.80	Liu et al 1989[94]	At mean pressure Units: mL/mm Hg
	Whole body	Normotensive	Av. 33	M/F	112/74	2.15	Ting et al 1995[95]	At mean pressure Units: mL/mm Hg
	Whole body	Hypertensive	Av. 33	M/F	161/100	1.03	Ting et al 1995[95]	At mean pressure Units: mL/mm Hg
	Whole body	Healthy	Av. 23	F	106/63	0.57	Rajkumar et al 1997[96]	Arbitrary units dimensionally equivalent to mL/mm Hg
	Whole body	Healthy	Av. 60	F	123/82	0.34	McGrath et al 1998[97]	Arbitrary units dimensionally equivalent to mL/mm Hg
	Whole body	Healthy sedentary	Av. 26	M	109/63	0.54	Bertovic et al 1999[98]	Arbitrary units dimensionally equivalent to mL/mm Hg

(*continued*)

Table 2. Indices of arterial stiffness and reference values

INDEX	Artery	Condition	Age	Sex	Pressure	Value	Reference	Comments
	Whole body	Strength trained athletes	Av. 26	M	120/59	0.40	Bertovic et al 1999[98]	Arbitrary units dimensionally equivalent to mL/mm Hg
	Whole body	Postenenopausal	Av. 59	F	126/71	0.26	Rajkumar et al 1997[96]	Arbitrary units dimensionally equivalent to mL/mm Hg
	Whole body	Postenenopausal	Av. 63	F	126/69	0.31	Waddell et al 1999[99]	Arbitrary units dimensionally equivalent to mL/mm Hg

Ao = aortic; Av. = average; B = brachial; C = carotid; CAD = coronary artery disease; Desc. = descending; F = female; Fem = femoral; M = male; N/A = not available; R = radial.
* These indices are site specific and vary with distending pressure.

ultrasound/catheter tip manometer tip system introduced by Stefanadis et al.[22] Similar approaches can be applied noninvasively at different sites. Diameter change, although small, can be measured accurately,[17–19] but there are problems in estimation of pressure change at the same site. Amplification of the pressure pulse along the arterial tree is not the only problem.[6] Inaccuracy of all cuff sphygmomanometer systems[23,24] is another.

In measurements of pressure and diameter, stiffness (Table 1) can be expressed as: Distensibility, Compliance, Elastic modulus (Peterson), Elastic modulus (Young). Distensibility is the relative change in diameter with pressure, compliance is the absolute change in diameter (or volume) with pressure, elastic modulus is pressure change required for (theoretic) 100% increase in diameter, and Young's modulus is pressure change per square centimeter for (theoretic) 100% extension. The different indices, as discussed at the 1994 ISH Satellite Meeting are described in Table 1. Table 2 gives normal values as determined in multiple studies.

The most hallowed (and still probably the best) measure of arterial stiffness is pulse wave velocity (PWV).[2,6,25] This quantity is related to the Young's modulus (E) of a thin-walled homogenous elastic tube by the formula: $PWV = \sqrt{E \times h/2r\rho}$, where ρ is the density of fluid within (blood is approximately 1.05) and h/2r is the wall thickness/diameter.[6]

Pulse wave velocity is measured as the difference between two recording sites in the line of pulse travel, and the delay between corresponding points on the wave (of pressure or of flow), which are not influenced by wave reflection. The wave front or initial upstroke is the usual point of reference in the two waveforms.[25]

Practical problems in measurement of pulse wave velocity arise when convenient points of measurement (eg, carotid and femoral artery) are not in the same line of travel, and in determining the actual arterial distance between recording sites from measurements on the surface of the body. Pulse wave velocity in large central elastic arteries such as the aorta increases markedly with age, whereas that in upper limb muscular arteries PWV does not increase (Fig. 3A).

Characteristic impedance is another valuable index of arterial stiffness, and relates absolute arterial pressure at a site to absolute velocity of flow at the same site in the absence of wave reflections.[6] Characteristic impedance (Zc) is related to PWV by the formula $Zc = PWV \times \rho$. Because ρ (density of blood) is approximately unity, these values are numerically almost identical when expressed as centimeters per second and as dyne second per cubic centimeters.[6] It is difficult to measure characteristic impedance by noninvasive methods because of the difficulties in excluding effects of wave reflection, and the compounding of errors in measuring noninvasive flow and noninvasive pressure.

Because all values of arterial stiffness are pressure

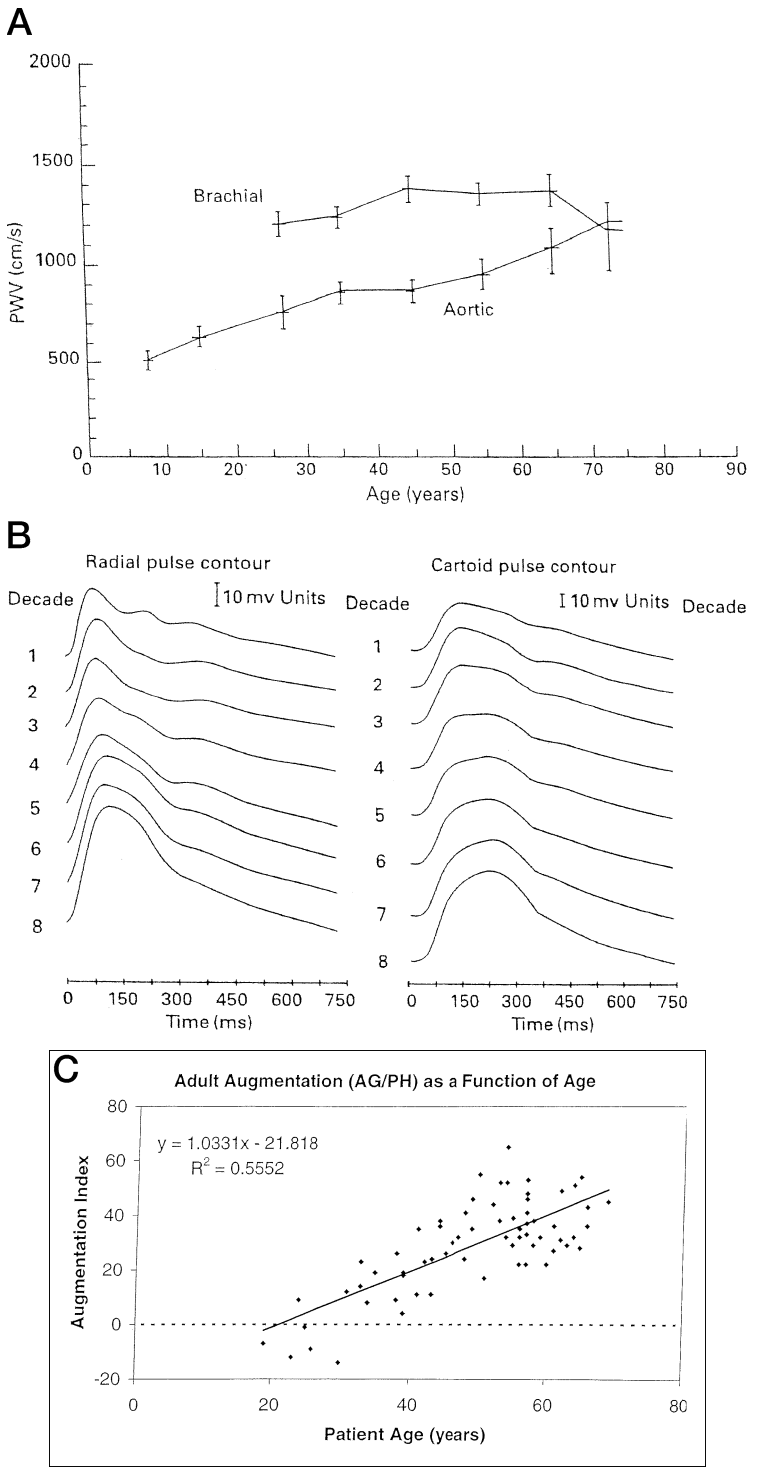

FIG. 3. Age-related changes in apparently normal populations. **A**) Brachial and aortic pulse wave velocity (Australian cohort). (Reprinted with permission from Ho K: Effects of ageing on arterial distensibility and left ventricular load in an Australian population. BSc(Med) thesis. University of New South Wales, Australia, 1982.)[43] **B**) Radial (**left**) and carotid (**right**) pressure waveforms, plotted as ensemble-averaged waveforms by decade, in a cohort of 1004 normal Australian subjects. (Reprinted with permission from Kelly R, et al: Non-invasive determination of age-related changes in the human arterial pulse. Circulation 1989;80:1652–1659.)[27] **C**) Ascending aortic augmentation index (augmentation pressure/pulse height) in a combined group of US and Japanese patients with chest pain syndrome and normal coronary arteries, undergoing cardiac catheterization. From Murgo et al[44] and Takazawa.[32] **D**) Change in augmentation index (augmentation/pulse height) in the radial artery (**bottom line**) and carotid artery (**center line**), calculated from data in B, compared to the regression line for aortic augmentation index in C. **E**) Quartiles of systolic, diastolic, mean, and pulse pressure as a function of age in the original Framingham cohort. (Reprinted with permission from Franklin SS, et al: Hemodynamic pattern of age-related changes in blood pressure: the Framingham Heart Study. Circulation 1997;96:308–315.)[40] PWV = pulse wave velocity; AG = augmentation; PH = pulse height.

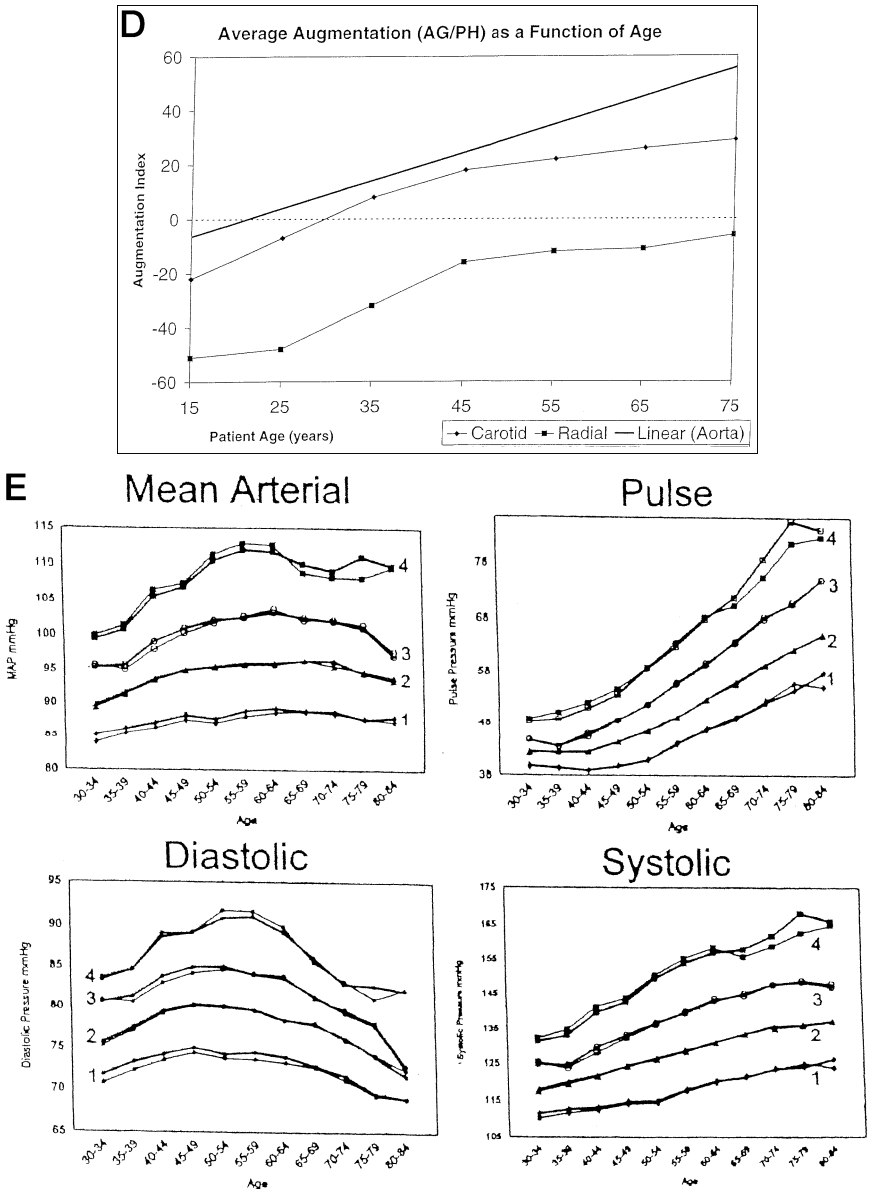

FIG. 3. Continued.

dependent, comparisons must relate to the same distending pressure. Attempts have been made to measure "isobaric" indices [16] or to adjust for the (almost) logarithmic relationship between stiffness indices and pressure.[26] Differences are often seen with differences in heart rate, but these are relatively small, at least in exteriorized arteries,[4,5] and are not apparent in determinations of PWV or characteristic impedance.

Manifestations of Arterial Stiffness

Manifestations of arterial stiffness include effects of stiffness on the arterial pressure (or flow) wave. The influence of stiffness is apparent on the arterial pressure wave recorded noninvasively by applanation tonometry in the radial or carotid artery (Fig. 3B). Change in stiffness is responsible for the characteristic changes in the pressure waves with aging,[27] and in the pressure wave that can be generated in the ascending aorta recorded directly (Fig. 2) or estimated from the radial waveform, using generalized transfer function techniques.[6,19]

The arterial pressure wave has two principal components—the wave generated by the heart, which travels away from the heart, and the reflected wave, which returns to the heart from peripheral sites, predominantly in the lower part of the body. Techniques exist for distinguishing these two components, and these are based on identification of the foot of the reflected wave, as this modifies the predicted initial wave contour. The time from the initial wave foot to reflected wave foot is generally less than the period of ventricular ejection, and therefore, is identifiable

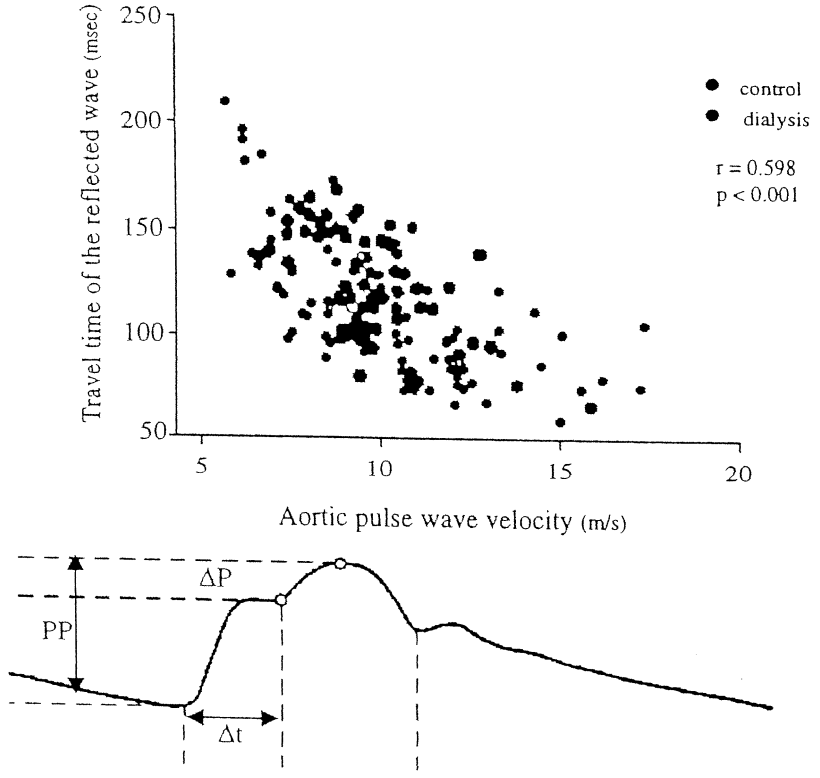

FIG. 4. Relationship between time from wave foot to initial systolic inflection of the carotid pressure waveform (ordinate), and carotid–femoral pulse wave velocity (abcissa). (Reprinted with permission from London G, et al: Increased systolic pressure in chronic uremia: role of arterial wave reflections. Hypertension 1992;20:10–19.)[28] Method of calculating time delay is illustrated as Δt. PP = pulse pressure.

in systole. This time is related to aortic pulse wave velocity (Fig. 4), [25,28] and can be used as an index of aortic PWV. Also useful is the increase in pressure after the reflected wave foot—the pressure wave augmentation during systole.[6,27] This is a manifestation rather than a measure of arterial stiffness, and represents the pressure boost with which the left ventricle must cope and which is caused by wave reflection. Aortic pressure wave augmentation can be measured from the transfer function process[6] or can be gauged directly from the carotid artery pulse.[6,19,27] It varies from less than zero at age 18 to a value approximating 50% of pulse pressure at age 80 years (Fig. 3C).[6,19] At any age aortic pressure wave augmentation is greater than carotid augmentation, and carotid augmentation is greater than radial augmentation (Fig. 3D). Augmentation varies with heart rate,[29] with heart failure,[6,30,31] and with drug therapy.[6,18] When factors are equivalent, it is a measure of arterial stiffness. When other factors are not equal, it is a manifestation of wave reflection. In the presence of heart failure due to systolic left ventricular dysfunction, any interpretation of pressure wave augmentation must consider the shape of the aortic flow wave.[6,30–32]

Another method of pulse wave analysis concentrates exclusively on the diastolic part of the arterial pressure wave, and seeks to separate the exponential pressure wave decay in a modified Windkessel model from the effects of the damped sinusoidal wave caused by wave reflection.[24,33] This is difficult when most of the wave reflection is in systole rather than in diastole, and when the position of the reflected wave can increase or lower pressure at the point where diastole is taken to start, and from which the exponential decay is calculated. Other problems with this approach include failure to consider the difference (usually about 12 mm Hg) between end-systolic pressure in central and peripheral arteries, and the need to estimate cardiac output from the pressure wave itself. (In validation studies of one device there was a better correlation between a line horizontal to the measured flow axis than the regression line to data points relating estimated and measured

Table 3. Relationship between components of arterial pressure and coronary heart disease risk at different ages; Framingham initial cohort and offspring study[36]

	Age <40	40–49 Years	50–59 Years	60 Years
DBP	1.54‡	1.28†	1.14*	1.12
SBP	1.16*	1.15†	1.09†	1.17‡
PP	0.84†,+	1.16	1.12*	1.24‡

DBP = diastolic blood pressure; SBP = systolic blood pressure; PP = pulse pressure.
Hazard ratio/10 mm Hg.
* $P < .05$; † $P < .01$; ‡ $P < .001$.
+ in males 0.71 (negative relation $P < .05$).

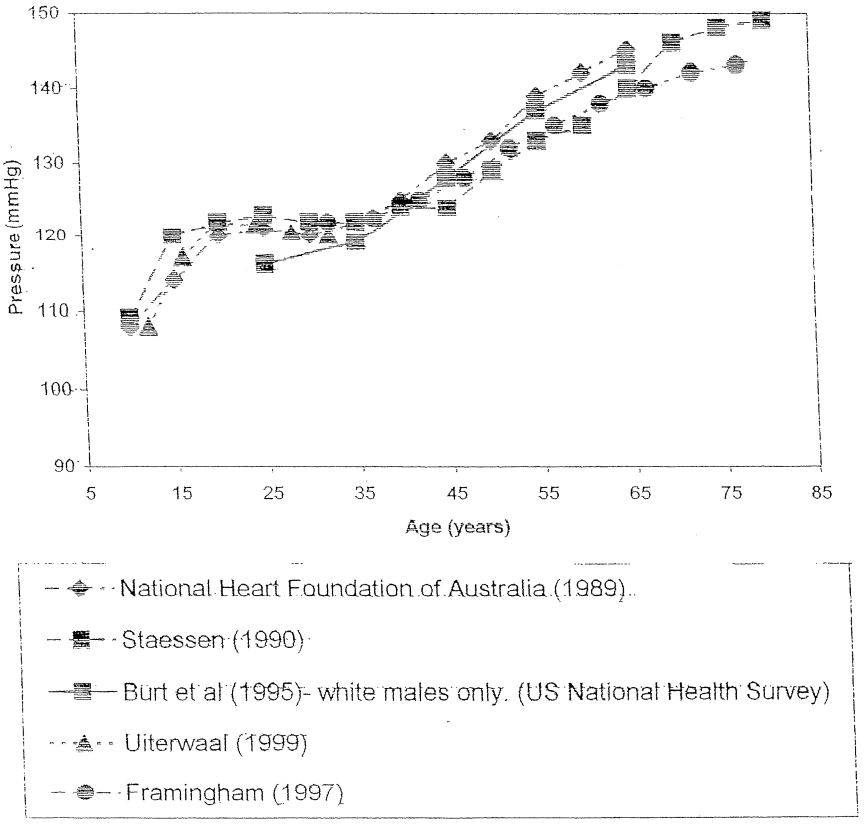

FIG. 5. Change in brachial systolic pressure with age shows a steep rise from age 10 to a plateau when full body height is reached at age 18,[41] then a subsequent rise after age 45 years. Data from National Heart Foundation of Australia,[46] US National Health Survey (white males),[46] Framingham,[40] Staessen et al,[45] and Uiterwaal et al,[41] summarized in reference 37.

flow.[24]) With respect to pressure measurement, at high heart rates, the level of the incisura, which corresponds to aortic valve closure in the radial artery, may be actually lower than end-diastolic pressure, therefore the estimate of exponential decay and total arterial compliance may become negative (Takazawa K, personal communication).

The method for calculating total arterial compliance[34] also requires noninvasive estimation of cardiac output and assumption of a Windkessel model of the arterial tree in which no wave reflection exists.

Pulse pressure increases with age (Fig. 3E). Brachial pulse pressure has recently been confirmed as a robust index of cardiovascular events in persons aged more than 50 years.[35] In persons aged less than 40 years, this relationship ceases to be true, and in men less than 40 years there is an inverse relationship between brachial pulse pressure and coronary events (Table 3).[36] Such an apparent anomaly is readily explained on the basis of different amplification of the pulse wave between the central aorta and the brachial artery with age, and this is a manifestation of pulse wave reflection (Fig. 5). [37] In major studies, there is a plateau in brachial systolic pressure between age 17 years (when the body is fully grown) and age 40 years. At less than 17 years and more than 40 years, brachial systolic pressure increases steeply with age (Fig. 5).

This review is directed at arterial stiffness and its measurement, not at wave reflection and its implications. The two are related,[6,19] and to a large extent can be separated. The therapeutic effects of vasodilator drugs on conduit arteries appear to be most pronounced on arteries smaller than those described here[38,39] and are manifest as a reduction in wave reflection, with a decrease in pressure wave augmentation.[6,19,32] This needs to be discussed in a separate consensus conference.

Recommendations

1. As a generic term, stiffness is preferable, especially to compliance, which is more frequently used to describe adherence with therapy or advice, or adherence to protocol.
2. For regional measurements, diameter and pressure should be measured at the same point. When this cannot be done, note should be made of possible confounders, such as age, drugs, or heart rate.
3. For regional and other measurements, note should be made of distending pressure, and comparisons made at the same distending pressure. If technical correction for distending pressure is not possible,

validated statistical "adjustment" should be carried out and clearly described.

4. For indices that give absolute values, absolute initial size should always be given.
5. For global measures of arterial mechanics, analysis of the arterial pressure waveform is often performed. Although various techniques (and underlying models) are used, they should all take into account anterograde and reflected waves as important components of the measured waveform.
6. A preference is given to pure physical measures.
7. Reference values for all arterial properties must be given as a function of age.
8. Indices (Table 2) should be comprehensively applicable under different conditions.

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